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Satisfying the rural residential demand in Liberia with decentralized renewable energy schemes

Jose Alfaro*, Shelie Miller

Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan, 3012 Dana Building, 440 Church St., Ann Arbor, MI 48109, United States

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ABSTRACT

With the lowest access to electricity in the world, the country of Liberia, West Africa, has efforts underway for electrification through a fossil based centralized scheme around its capital city and possible connections to the larger Western Africa Power Pool network. These plans leave a large part of the rural population with no access to electricity.

This work analyzes the potential of decentralized generation to provide electricity to the rural Liberian population. The suppressed demand of the rural population is calculated at 235 GWh/yr. There is sufficient renewable energy potential to supply this demand. The capital costs and electricity prices of decentralized generation with different fuels are calculated and compared to the ability and willingness to pay of rural Liberians.

Small diesel units have the lowest capital cost but photovoltaic, small hydropower and small biomass projects provide lower electricity prices. Biomass and small hydro electricity are affordable for Liberians at \$0.08/kWh and \$0.11/kWh respectively. Diesel and photovoltaic, with levelized cost of electricity of \$0.62/kWh and \$0.33/kWh respectively, exceed Liberians' willingness to pay.

Centralized and decentralized electricity developments are not mutually exclusive; both may be used within a comprehensive electrification plan. Decentralized generation with emphasis on rural areas can complement the existing plans to achieve the Government of Liberia's goal of universal access to electricity, providing social equity and economic progress. In order to become a reality, rural decentralized electrification will need policy support and focused funding.

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* Corresponding author. Tel.: +1 734 764 1412.
E-mail address: jfalfaro@umich.edu (J. Alfaro).

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1. Introduction

1.1. Background

After a 14-year civil war, Liberia, West Africa, is moving towards redevelopment. With little remaining infrastructure and the lowest level of electrification in the world [1], the country seeks to reinvigorate its economy and provides general services to its population. Sub-Saharan Africa has been identified as the biggest challenge for development in the energy sector [2]. As Table 1 shows, Liberia has the largest electricity tariff and the lowest access to electricity in the region [1], highlighting the considerable challenges to electrifying its population.

A small diesel powered grid is available in the capital city of Monrovia, with electricity tariffs of $0.43/kWh [1]. Expansion of the centralized grid is under way. Electrification plans include expansion of diesel generating capacity, installation of heavy fuel oil generation, rehabilitation of a large hydropower plant at Mount Coffee, and integration to the Western Africa Power Pool (WAPP) [1]. Liberia is expected to join the WAPP by the year 2015 through a transmission project between Ivory Coast, Liberia, Sierra Leone, and Guinea (CLSG), and an additional low voltage connection to Ivory Cost [1].

The published electrification plans place emphasis on the urban and industrial sectors in Liberia but raise issues of demographic coverage, reliance on fossil fuels, and dependence on large centralized infrastructure. Centralized, fossil fuel based pathways like the one planned in Liberia have been shown to create environmental issues, external debt, social divides, and poor quality of service, leaving large segments of the population with no access to electricity [3,4]. In Liberia, urban areas will receive the majority of the benefits. More than 50% of the rural population in Liberia will remain with no access to electricity by the year 2040 [1].

The WAPP projects are key to Liberian electrification and will lower generation costs. Gnansounou et al. [5] state that integrating the electricity systems in the region will bring significant benefits through deferred capital investments, increased efficiency, and better reliability. However, the WAPP has been criticized for unrealistic goals and its lack of African ownership and clear objectives. As Pineau [6] notes, the level of integration and functionality to which the WAPP aspires has not been achieved by countries in the European Union or by the United States and the success of the WAPP given the lack of institutional capacity in the region is unlikely.

Table 1
Access rates and electricity tariffs in selected countries of West Africa.
Sources: [1,2,10,11]

Country	Liberia	Ghana	Ivory Coast	Sub-Saharan Africa	World
Access rate to electricity (%)	~1.6%[a]	60.5	47.3	28.5	79
Rural access rate (%)	< 2	23	18	11.9	65.1
Urban access rate (%)	0.58	85	78	57.5	93.6
Electricity tariff ($/kWh)	0.43	0.075	0.125		

[a] Estimated by authors from source data.

In the published plans, the Africa Energy Unit acknowledges these concerns and calls for efforts that run parallel to central grid and WAPP connections [1]. The Government of Liberia (GOL) has issued the National Energy Policy (NEP) and the Poverty Reduction Strategy (PRS) outlining a variety of development objectives, including "providing universal access to electricity" [7,8]. Further, it has established the Rural Renewable Energy Agency (RREA) to address rural electrification and undertake a National Rural Electrification Master Plan (REMP) [1,9].

Although analyses have been conducted on the economics and feasibility of the centralized grid, little attention has been given to the feasibility of supplying rural demand with renewable, decentralized electricity, which is the focus of this paper. This paper quantifies the suppressed electricity demand for the residential sector in rural Liberia and analyzes the possibilities for decentralized electricity generation. The suppressed demand is defined as electricity demand that would be present if service was available. The renewable energy potential in Liberia from different fuels is then estimated and an economic analysis of decentralized generation (DG) through these fuels is conducted. Solar photovoltaic (PV), small hydro, and biomass direct combustion are used as the feasible fuels in Liberia. Wind power is ignored due to low wind speeds throughout the country [10]. For comparison, the economics of small diesel fuel generation are presented due to its current use in rural areas of Liberia. The economic analysis includes overnight capital costs and simplified calculations of resulting levelized cost of electricity (LCOE). These costs are compared to the ability and willingness to pay of rural Liberians. Finally, tradeoffs of the fuel options are presented.

1.2. Reaching rural populations in Liberia

Grid expansion (GE) and decentralized generation (DG) are two methods that can be used to reach rural electrification goals. GE extends the centralized generation capacity by creating transmission and distribution networks to rural populations. DG uses smaller generation units located close to the rural load centers, avoiding large distribution networks. DG may involve the use of micro-grids joining a few communities or load centers and may eventually be connected to a larger grid.

Due to the current electrification plans in Liberia and the lack of existing centralized infrastructure, this paper places emphasis on DG for rural areas. DG is more economical than GE in situations with low population density, low electricity demand per person, lack of centralized generation infrastructure, and difficult terrain [1,2,11,12]. Zerriffi and Wilson [13] point out that the scalability of DG is particularly well suited for the low demand and sparse population of rural areas. Further, Levin and Thomas [14] use an algorithm to determine the optimum economic choice between DG and GE for each load center in a series of countries. When the algorithm is applied to Liberia, DG is more economical for 72–77% of the population and 95–98% of the load centers [14]. This distribution reflects the urban and rural demographics of Liberia, with the capital city of Monrovia being the only truly urban center and holding around 28% of the population [15].

1.3. Available renewable energy resources in Liberia

The solar potential in Liberia is strong throughout the country. No direct measurements of insolation are available, but satellite data establishes horizontal surface insolation at 208.5 W/m^2 [1].

Liberia has rainfall in the range of 1600–4000 mm/yr [9,16]. Studies have shown that medium hydro projects have a potential of over 400 MW on the Cavalla and Tiboto Rivers alone [17]. These rivers require bilateral cooperation with Ivory Coast and Sierra Leone, but 24 other possible sites have been identified for small to medium hydropower [1]. There are also opportunities for micro and pico hydro projects.

Although more than 99% of the population of Liberia depend on charcoal for cooking and heating needs, significant amounts of biomass residues are available that would not hinder the production of traditional fuels or food. Electricity production depends on conversion efficiency of the technology used, which can range from 20% to 40%, but a study by the National Renewable Energy Laboratory assumes 1–2 GWh of electricity per tone of biomass [16]. This paper considers only food and cash crop waste, although other sources of biomass are available. Milbrandt estimates the present potential of these residues at 5121 GWh/yr [16].

2. Methods

2.1. Estimating demand

The Liberian electrification situation is particularly novel. Historical data is often a key component of electricity forecasts. Due to the drastic and disruptive impact of the civil war, historic data are not useful to project econometric values, energy use, and demographic trends. Liberian rural residential electricity demand is estimated in this paper using population growth, yearly increase in connections (or increase in access to electricity), and increase in demand from people already receiving electricity. These are the same drivers used by the World Bank for urban residential areas in Liberia [1], but are modified with data specific to the rural areas. The model begins with current data and creates a forecast of demand in the year 2050 with Eqs. (1)–(4).

A computer programming software called Netlogo is used for the model. Netlogo is common in Agent Based Modeling applications (ABM) [18], but its ability to create stochastic scenarios makes it a good tool for this work. Utilizing the "BehaviorSpace" tool included in the software allows users to perform thousands of experiments in short periods of time and easily creates Monte Carlo simulations

$$D_{T0} = D_R * AR_0 * P_0 \tag{1}$$

where D_{T0} is the total initial demand, D_R is the typical demand in rural areas per person, AR_0 is the the initial rural electricity access rate in percentage, and P_0 is the initial population.

Each time step of the model the total demand becomes

$$D_{Ti} = D_R * AR_i * P_i + D_{Ti-1} R\% \tag{2}$$

where D_{Ti} is the total demand in year i, AR_i is the rural electricity access rate in year i, P_i is the population in year i, and $R\%$ is the yearly rebound %, and

$$AR_i = AR_{i-1} * (1 + AR_{inc}) \tag{3}$$

$$P_i = P_{i-1} * P_{inc} \tag{4}$$

where AR_{inc} is the yearly percent increase in rural electricity access and P_{inc} is the annual percent population growth.

The software also provides an intuitive graphic user interface, and an easy installation package for possible new users. Netlogo makes it easy to monitor parameters and makes clear to users the variables involved in the analysis. A screen shot of the model can be seen in the Supporting information.

A Monte Carlo simulation is performed with the BehaviorSpace tool. Two thousand experiments are conducted to determine the expected results of electricity demand, capital costs, levelized electricity prices, and total rural population served. The parameter ranges presented in Table 2 were used to create triangular distributions with a mode equal to the mean of the parameter range. This approximation was chosen due to the scarcity of data. For each experiment, the model stochastically chooses a value from the distributions to perform the calculations.

Parameter data comes from Liberian census and world estimates of rural electricity demand. The latest Liberian census indicated that 2.5 million people lived outside of the greater Monrovia area in 2008 [15]. These values are used as the initial parameters in the model. Liberian population has increased at a rate of 2.8% over the past 5 years [19], and is assumed to continue at this rate throughout the study period to year 2050. The increase in demand is estimated at 1.5% according to assumptions made by the World Bank in their recent studies of the Liberian urban case [1]. Average demand of electricity per person in rural populations is estimated at 50 kWh/yr. This value is typical in cases similar to Liberia's [2] and is conservatively high when compared to other studies in developing countries [14,20,21].

Since increase in access to electricity can largely depend on policies and available investment, the paper assumes a range of 1–2%. This ensures that over 50% of the rural population is reached, capturing the population not serviced by the central grid plan.

2.2. Estimating capital costs

Overnight capital costs ignore the time lag of constructing a project and place the cost in present time. Here they are calculated using world averages for the different technologies. Although world averages are only a proxy, data collected from biomass and small hydro pilot projects currently under way in Liberia shows that costs are in line with world averages for those technologies [1,22,23]. For PV projects, conversations with suppliers in Liberia suggest capital costs can be 60% higher than world averages when purchasing individual components from a retailer (Union Strong Company, personal communication, 08/2012). This paper assumes that a public or private solar PV project of larger scale would encounter values more in line with world averages.

Transmission, distribution, and home connections are expected to be similar for all technologies and are not included in the capital cost calculations. Eq. (5) is used to calculate the capital costs of

Table 2
Parameters for estimate of demand.

Parameter	Upper limit	Average	Lower limit	Sources
Yearly population increase (%)		2.8		United Nations (2011)
Increase in access to electricity (%)	2	1.5	1	Assumed
Increase in electricity demand by electrified populations	2	1.5	1	Africa Energy Unit; International Energy Agency[a]
Electricity demand	60	50	40	International Energy Agency[a]

[a] Source provides average value; upper and lower limits are defined as ±20% of the average.

biomass, small hydro, and small diesel generation

$$C_i = \frac{D_T * CC_i}{8766\ \text{h} * DF_i} \quad (5)$$

where C_i is the capital cost of technology i (for hydro, biomass, and diesel), D_T is the total electricity demand for rural areas in kW, CC_i is the unit capital cost for technology i in $/kW, and DF_i is the duty factor (actual output compared to nameplate capacity) for technology i.

In the case of solar PV technology capital costs do not include a duty factor but depend on insolation values. Also, unit capital costs are given in $/Wp, a metric that includes the efficiency of the panels. Solar capital cost then becomes

$$C_s = \frac{D_{Ti} * 1000\ (\text{W/m}^2) * CS_s}{I * 8766\ \text{h}} \quad (6)$$

where C_S is the capital cost for solar PV, CC_S is the unit capital cost for solar PV in $/kWp, and I is the insolation in Liberia in W/m^2

2.3. Estimating price of electricity

For each technology, a levelized cost of electricity is calculated including capital costs, fixed operation and maintenance costs, variable costs (fuel), and duty factors. The calculations in this paper represent a simple analysis of this metric. Eq. (7) is used for the calculation and Tables 2 and 3 are a summary of the data and sources for the calculations

$$P_{ei} = \frac{CRF_{eff} * CC_i}{8766\ \text{h} * DF_i} + HR_i * P_f^* + O\&M_i \quad (7)$$

where P_{ei} is the levelized price of electricity of technology i in $/kWh and CRF_{eff} is the effective capital recovery factor including taxes and insurance:

$$CRF_{eff} = \frac{d}{[1-(1+d)^{-n}]} + T\&I$$

d is the discount factor, n is the operational life of unit (15 years for solar PV and 30 for all other technologies), T & I is the taxes and insurance, and HR_i is the heat rate of fuel for technology i in Btu/kWh, P_f^* is the levelized price of fuel $= (d/(d-j)) * P_f$, where P_f is the price of fuel in $/Btu, j is the price levelizer assumed at 2%, $O\&M$ is the operation and maintenance cost of technology i in $/kWh.

Sensitivity analyses are conducted through one at a time perturbation of the parameters in the model. Parameters are changed by ±20% from their mean. This sensitivity analysis shows the parameters where uncertainty is most likely to create a large deviation from the calculated results.

2.4. Gathering renewable energy potential data

Biomass potential in Liberia is presented in the report published by [16]. Small hydro potential is estimated by utilizing only the small sites mentioned above. A 40% duty factor for these projects is assumed. An efficiency of 10% and an insolation of 208.5 W/m^2 are used for PV projects [1]. The model assumes the use of 0.01% of the Liberian area for PV production, around 10 km^2, with an average of 6 h/day of sunshine [10].

2.5. Estimating ability to pay monthly electricity bills

Winrock International conducted a survey on a small sample of the population in Liberia [22]. The survey results are used here for the determination of expected monthly electricity bills and customers' ability and willingness to pay. This survey is the only available study in the literature that examines these parameters for the Liberian rural case.

The survey sample comes from a relatively populated area in Bong County, near a mini-hydro pilot project. Residential customers, small businesses, and a few large institutions are included in the sample. The results of the Winrock surveys show the high costs of electricity options and the available commercial demand that can help to justify larger generation schemes like the micro-hydro project being funded by USAID [22,23].

According to answers provided by the residential customers, the ability and willingness to pay of Liberian households is $10/month [22]. This is lower than the actual fuel expenditures of Liberians. The survey shows that households spend an average of $13 per month on lighting alone. Liberians use high cost options such as kerosene lamps ($1.53/kWh), car batteries ($8.43/kWh),

Table 3
Parameters for cost and levelized price of electricity calculations.

Parameter	Upper limit	Average	Lower limit	Sources
Solar PV				
Solar capital Costs ($/kWp)	4100	3400	2700	[25]
Solar O&M ($/kW)	14.02	11.68	9.34	[25][a]
Insolation (W/m^2)	250	208.5	167	[1]
Small hydro				
Hydro capital Cost ($/kW)	2400	2000	1600	[1, 26]
Hydro O&M ($/kWh)	0.04	0.025	0.01	[25]
Hydro duty factor (%)	60	40	20	[25][a]
Small biomass				
Biomass capital cost ($/kW)	4100	3350	2600	[25]
Biomass O&M ($/kW)	77.34	64.45	51.6	[27][a]
Biomass fuel costs ($/ton)	3	2	1	[28] Source provided an average, authors create 50% limits around it
Biomass duty factor (%)	90	80	70	Assumed
Biomass heat rate	19	17.5	16	[17, 29]
Small diesel				
Fossil capital cost ($/kW)	720	600	480	[30]
Fossil O&M cost ($/kWh)	0.024	0.02	0.016	Assumed after review of HOMER Micropower Optimization community website [31]
Fossil fuel consumption (gal/kWh)	0.143	0.119	0.095	[30][a]
Fossil fuel costs ($/gal)	4.80	4.00	3.20	Authors' observations in Liberia
Fossil duty factor (%)	90	80	70	Assumed

[a] Source provides average value; upper and lower limits are defined as ±20% of the average.

dry cell batteries ($74.01/kWh), candles ($8.27/kWh), and household diesel generators ($3.96/kWh) [1].

Winrock's survey found that the average household in this particular area has 8.7 people, higher than the national average of 5 [15]. This translates to a yearly demand of 435 kWh/household when using an average demand of 50 kWh/pr/yr. Prices of electricity determined with Eq. (7) are used to determine the monthly bill of a household connected to each technology.

3. Results and discussion

3.1. Main results

The estimated Liberian demand for rural residential electricity in 2050 is 235 ± 75 GWh/yr to service $61 \pm 33\%$ of the rural population's total demand. This exceeds the level needed to complement the existing electrification programs and achieve the universal electrification goal of the GOL. A similar level of electricity consumption would power around 6800 US households [24,25].

Table 4 compares the estimated demand to the available renewable energy potential. The solar and biomass potentials in Liberia are large enough to supply the expected demand. These technologies are particularly useful since their location can be planned near the load centers for decentralized schemes. Small hydro can cover more than 98% of the expected demand. Hydropower presents the logistical constraint of having fixed geographical location.

The overnight capital costs calculated in Eqs. (5) and (6) can be seen in Fig. 1. These are the costs that would be incurred to fulfill the estimated demand by using each technology exclusively. Although a combination of technology options is more likely, Fig. 1 provides cornerstone scenarios for the total amount of capital investment that Liberia would need to provide their rural population with electricity in a decentralized scheme. Further, it shows a relative cost comparison for the Liberian renewable energy options.

Fig. 1 shows that renewable energy technologies involve a significantly larger capital investment when compared to diesel.

Table 4
Estimated electricity demand in 2050 and renewable energy potential in Liberia.

Liberian Electricity demand by year 2050 (GWh/yr)	Small hydro potential (GWh/yr)	Solar PV potential (GWh/yr)	Biomass potential (GWh/yr)
235 ± 75	231	457	5121

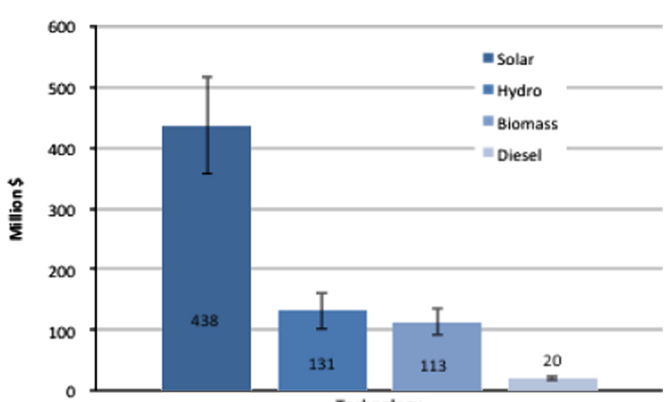

Fig. 1. Overnight capital cost to fulfill expected demand in 2050.

However, the technologies should also be compared on the grounds of resulting electricity tariffs, or levelized cost of electricity (LCOE). LCOE normalize fixed and variable costs of a project with the lifetime energy output of the project, i.e. $/kWh. For solar PV the lifetime of the project is estimated at 15 years to reflect the expected life of solar components. All other technologies have an assumed lifespan of 30 years.

LCOE provides a broader picture for decision makers when compared to overnight capital costs. Stakeholders can consider both metrics to pursue an appropriate technology. When considering this broader picture all the renewable technologies are more affordable than the diesel option. Expected levelized costs of electricity (LCOE) can be seen in Fig. 2.

Model results for LCOE can be validated with recent world averages developed by the International Renewable Energy Agency (IRENA). Solar PV systems, with storage included, have a LCOE in the range of $0.36–$0.71/kWh for systems of less than 5 kW of installed capacity [26]. Larger systems achieve costs as low as $0.26/kWh [26]. The model results of $0.33/kWh are plausible given the paper's assumption of purchasing components in bulk for community size projects. For small hydro projects, model results of $0.11/kWh agree with IRENA's empirical data of $0.02–$0.10/kWh, with pico schemes as high as $0.27/kWh [27]. For biomass boilers and gasifier technologies, IRENA provides a range of $0.06–$0.24/kWh. The model's result of $0.08/kWh is at the low end of the range provided. However, IRENA finds lower costs where local food and cash crop wastes are readily available as feedstock, which is the situation in this analysis [28].

Fig. 3 shows the cost of a consumer's monthly bill under each technology. The costs of biomass and small hydro electricity are below Liberian willingness to pay of $10 per month. Biomass and small hydro electricity prices are also lower than the tariff for electricity from the centralized grid present in Monrovia and the best-case scenario calculated by the African Energy Unit for the expansion of that grid of $0.12/kWh [1]. PV is not explicitly under

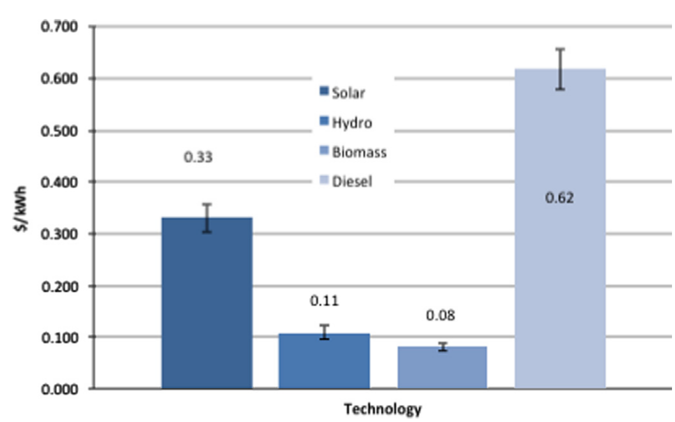

Fig. 2. Levelized prices of electricity.

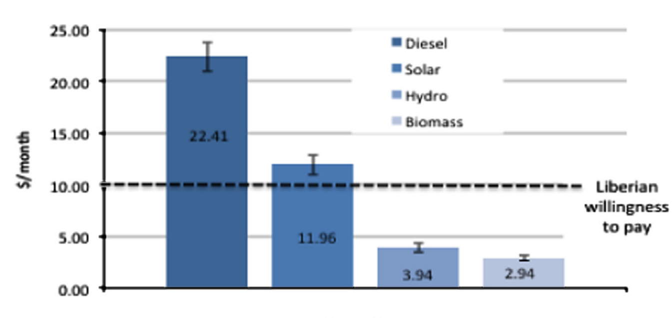

Fig. 3. Monthly costs of electricity for each technology

the willingness to pay of the Liberian sample population but it is affordable compared to the present expenditures of Liberians for lighting services of $13 per month.

All three renewable technologies provide monthly bills in line with reported acceptable costs. Winrock expects a 50 W connection to the pilot micro-hydro project to charge $6 per month and a 100 W connection $13 per month [23]. Diesel generation does not appear to be affordable for Liberian consumers since monthly bills would be more than 100% higher than the stated willingness to pay of consumers in the Gbanga region.

3.2. Sensitivity analysis

One at a time perturbation of parameters allows the identification of areas of sensitivity in the model. Particular attention is paid to significant correlations that affect the main results of the work: total expected electricity demand, total expected capital costs, and LCOE.

Total expected electricity demand has a strong direct correlation with population growth and average household demand. A change of 20% in population growth causes a change in total electricity demand of almost 25%. A change of 20% in household demand causes 20% change in demand. Increase in consumption of connected populations does not significantly affect the results.

Total expected capital costs of each technology have a strong indirect correlation to duty factors (insolation in the case of PV). When technologies operate at a lower duty factor a greater installed capacity is required to fulfill the demand. Duty factors also cause the greatest change in LCOE for all technologies. A decrease in duty factor means that less electricity is being produced each year and the total fixed cost of the project is normalized to a lower number of energy units produced.

As expected, changes in technology capital costs per kW have a direct correlation to LCOE. However, the change is less than 1:1.

Hydropower costs show significant sensitivity to duty factors. Decision makers should be aware that climatic events could highly influence the electricity prices for this technology. For example, a reduction in river flow would impact the duty factor of the technology increasing electricity prices.

Biomass technologies display stable electricity prices. A wide range of feedstocks is available in Liberia, making it easier for biomass projects to maintain stable supply and costs. Changes in heat rate and feedstock prices do not significantly change the tariffs calculated. Although the LCOE is sensitive to duty factor, it is easier to control this parameter with biomass technology as long as there is demand. Crops can be stored with appropriate techniques for later use in electricity production, allowing inventory management and on-demand generation.

Diesel LCOE shows a direct correlation with fuel consumption. A 20% change in fuel consumption causes a 19% change in electricity prices. Generation units of lower quality and fuel efficiency would increase the already high LCOE of diesel. This result agrees with the fact that the largest share of diesel costs comes from fuel prices.

Graphs for each group of parameters evaluated during the sensitivity analysis can be found in the Supporting information.

3.3. Fuel accessibility

Fuel supply logistics are keys in electrification. In the case of fossil fuels, Liberia lacks sufficient infrastructure to import, store, and transport fuels [1,29]. Transporting diesel for electricity production would increase prices and add pressure to the transportation system.

Renewables, on the other hand, have the benefit of being located close to the point of use. Solar insolation is high throughout the country. However, transportation of solar panels and other equipment related to solar PV projects would add significant cost to an already expensive technology.

Hydro projects can generally be placed near load centers. Turbines and other parts can be created locally if the technology and knowledge are appropriately transferred [30]. This allows for small hydro projects to avoid the logistical issues involved with transportation.

Biomass residues are already located in areas of potential electricity loads. Liberia's soil, climate, and fallow arable land allow for easy location of coupled farming and electricity production projects. However, the residues are scattered in fields and must be collected and transported to a generation site. Collection efforts should be planned appropriately with farmers and communities to avoid price increases.

3.4. Intermittency of renewables

Electric projects need to be reliable for communities to achieve full benefits. A study by Kooijman–van Dijk shows that blackouts affect the uptake of electricity and increase the problems faced by enterprises that adopt it [31]. Predictability of blackouts allows enterprises to adapt to the supply [31]. Renewable energy projects with insufficient or intermittent supply should provide transparency to their customers communicating hours of operation and expected black outs. An example of a proper arrangement is the micro-utility that services a market in Bangladesh. This utility proved successful by using a 5 h per day arrangement [32].

Alternatively, more than one technology can be used. A Solar PV array could have a back-up thermal generator, whether fossil or biomass based. Hybrid systems for continuous supply are a promising way of leveraging the advantages of each technology while keeping capital costs and user tariffs low. Ref. [33] finds that in Bangladesh hybrid systems using PV and diesel generation together form the only economically feasible option for the region studied.

Storage solutions can also be pursued to enhance the performance of renewables and availability of electricity. Batteries are widely used in Liberia to store power created by diesel generators. Examples are available in developing countries where deep cycle and car batteries are used to provide electricity to households. Batteries are charged at a central location in the community and each family transports it back to their homes for use. This practice has even been used to model economic performance of generation projects [20].

Connecting renewable energy projects in remote areas to the grid can also form a hybrid system. A transmission line that connects a DG project to the closest section of the grid can allow the grid to act as a storage device through a net metering program. The grid can buy energy from the renewable project during peak hours but sell electricity to the project when renewable energy may not be available. The electricity produced during peak hours by the renewable projects can help to alleviate supply constraints on grid. This set up was modeled for a system in a remote island in India. The availability of the grid as a back-up and storage device made the renewable energy projects financially viable while providing extra electricity supply to a grid with high demand [34].

3.5. Comparative summary

Table 5 offers a comparative analysis of each technology. Although biomass has a high technology capital cost per kW relative to the other technologies, it affords the cheapest LCOE for the users and is a stable source of electricity generation. Because of its performance, the total investment to supply all Liberia's modeled demand is the cheapest of the renewable energy options as seen in Fig. 1. The stability of its electricity prices and

Table 5
Comparative analysis of decentralized generation technologies.

Generation technology	Diesel	Solar	Hydro	Biomass
Average capital cost	$720/kW	$3400/kWp	$2000/kW	$3350/kW
Levelized electricity price ($/kWh)	0.62	0.33	0.11	$0.08
Stability of electricity price	Highly variable particularly due to fuel consumption	Variable due to climate conditions	Variable due to climate conditions	Stable due to flexibility of fuel and heat rates
Duty factor	Stable	Variable	Variable	Stable
Fuel access	Complicated in rural areas due to little road infrastructure	Simple	Limited to potential locations close to loads	Variable, fuels already close to loads but must be collected from fields
Maintenance capacity	Available	Lacking	Available	Available
Susceptibility to intermittency	Low	High	Medium	Low

duty factors allows generators to create appropriate forecasts for a clear fee-for-service approach with lower uncertainty.

Biomass fuel availability is good in Liberia and located near load points. Because electricity prices for this technology are stable with regard to the energy content or heat rate of the fuel, different cash and food crop residues already on the ground can be utilized avoiding a competition with food supply. The large amount of fallow agricultural land in Liberia allows for careful planning of combined food and energy projects if desired. The situation in Liberia is consistent with results that find that Africa and Latin America have superfluous land to meet the energy requirements of their populations even when forested lands are taken out of the equation [35].

The use of residues represents an income opportunity for farmers and rural communities. Agriculture is considered as one of the keys to sustainable development in Liberia and more than 70% of the population depends on it for their income [8,16]. It may also create a separate market for non-traditional agricultural products.

Biomass is a better economic driver when compared to other electrification projects. In Uganda, biomass projects create four times the economic flows within the community when compared to small diesel, grid connected hydro, and solar panels [20]. This evidence is supported also by experiences with projects in India [36].

The technical and human capacity in the country should be considered when deciding on electrification technologies. Diesel generators are common in Liberia and the knowledge necessary for their maintenance is available. The level of knowledge required for PV technologies is lacking. Hydro and biomass technologies are more mature and their maintenance is similar to diesel and other applications present in Liberia. This makes them less susceptible to the lack of human capacity for their service and operation.

3.6. *Decentralized electricity as an economic development tool*

It is well documented that DG provides economic, social, and environmental benefits in rural areas, moving populations out of poverty, creating wealth, protecting the environment, and catalyzing development [4,31,37–39]. But to achieve sustainable development, other components must be present. Ref.[40] analyses the experience of the Norwegian Aid program in the energy sector of developing countries and concludes that while electricity is necessary for development, it is not sufficient and investment in other infrastructures is required alongside electrification efforts. Ref. [41] states that in 11 out of 17 African countries studied electricity consumption was only a contributing factor to growth. Their results identify capital and labor as more important for increases in economic production. Similar results were obtained by [42] in six Central American countries where an increase in labor force was more important than energy consumption in gross domestic product growth.

Because of this some countries, such as Cuba, have created efforts that include electrification inside a more general development agenda [43]. The question remains on how to identify the priorities for development in different countries. Ref. [44] uses a linguistic approach to enhance the technology needs assessment and characterize the priorities for energy improvements in developing countries. They find that providing electricity to households is among top priorities in countries like Israel, Kenya, Chile, and China. They also find that where electricity distribution is not well-established electricity for households appears as a top priority. This emphasis is not present in countries with good electricity distribution systems and good household accessibility pointing to the importance of electricity for the residential sector in developing countries.

After the war Liberia created a Poverty Reduction Strategy (PRS) with four reinforcing pillars, expanding peace and security, revitalizing the economy, strengthening the rule of law, and rehabilitating infrastructure and delivering basic services [8]. Electricity supply applies directly to three of those pillars. Further, ensuring electrification of rural populations is key in reducing inequality in the country as expressed in the PRS. Liberians identified the rebuilding of roads as the number one development need during PRS consultation meetings. Roads were viewed as essential for improvements in education, access to health care, better governance, and revitalization of agriculture [8]. However, the electrification of rural areas is still a necessary condition for improvements in many of these development goals and others such as the millennium development goals.

Because of this, investment in electrification and ensuring that rural and urban areas receive equal opportunities for electricity services can be viewed as an opportunity for accelerating development. Examples of the use of electricity and particularly rural electrification schemes as catalysts for economic growth and prosperity are present around the world. In Bangladesh and Nepal the establishment of cooperatives for rural electrification resulted in other services for the communities like micro-finance and technical training [45]. Statistical analysis of the Liberian situation suggests that the economy is driven by labor, petroleum, electricity and capital [46]. But the analysis also shows that electricity can be a substitute for petroleum allowing Liberia to pursue electrification as a major piece of economic development.

Renewable energy schemes in particular can be used to build capacity and economic activity in the country. Local industries have been created out of rural electrification projects. For example, turbine designs from German and Swiss aid projects were transferred successfully to Peru, Sri Lanka, Nepal and Indonesia where local manufacturers and workshops took on the business [30]. This is particularly useful in Liberia where the lack of technical knowledge represents a good opportunity for development organizations to provide vocational training, new job opportunities, economic activity, and electric supply.

3.7. Financing projects

Recent literature suggests that successful approaches to rural electrification often require subsidizing of the capital equipment by donor agencies or the national government [1,38,47]. A combination of subsidies, grants, and cost recovery through fee-for-service schemes can be used. In South Africa, several fee-for-service solar power concessions have thrived using these methods, even in the face of uncertain government subsidies and encroachment by the national utility through grid connections in the concession areas [48]. A similar approach in Zambia has resulted in successful rural electrification companies [49].

Renewable energy projects can also be financed through mechanisms available for climate change mitigation. The Clean Development Mechanism (CDM) established by the United Nations provides a vehicle for developing countries to receive financing from developed countries for projects that can reduce carbon emissions that would occur without the aid [50]. This makes capital recovery and financing easier for both public and private enterprises.

Civil societies can take advantage of climate mitigation schemes as well. For example, a community cooperative or non-government organization can use the Global Environmental Facility Small Grants Programme [51]. This program allows the community groups to establish a project of up to $50,000. Given the average values in Table 2 for small biomass, a community can afford up to 15 kW of biomass production or 65 MWh/yr of electricity assuming a duty factor of 0.50. A typical village cluster in Uganda of 250 households, several small businesses, a school, and medical center consume close to 20 MWh/yr [20]. Examples of such grass roots cooperatives have been successful in Tanzania and Costa Rica [47,52].

3.8. Industrial loads

This paper does not include the commercial and industrial loads in rural Liberia. Several concessions for mining, rubber, palm oil and logging are present or expected in the near future and have been taken into consideration in the centralized grid plan [1]. In developing countries, these companies usually pursue self-generation of power, even when a utility is present, due to the instability of electricity generation [53,54].

Decision makers may leverage the capability of these companies for self-generation. Any spare capacity may be purchased by small power projects and used as back-up. As the power generation in the country improves, companies may rely on small connections to the emerging grid as a way to abandon self-generation gradually.

The presence of industrial loads is a good opportunity for the government to create public–private cooperation. The cost of self-generation is high [53]. Decision makers can help these industries coordinate with local populations to create generating alternatives that would enhance the livelihoods of populations and lower the cost of the industry's power supply.

4. Conclusions

This paper responds to the gap in the literature on the rural residential demand in Liberia. It shows that Liberia's renewable energy potential is large enough to satisfy the rural residential demand. Results also show that renewable fuels in Liberia provide lower LCOE than diesel but require a higher capital investment. Hydropower and biomass can provide electricity at acceptable prices for the rural population. Biomass technologies in particular offer significant benefits in the Liberian context. Diesel and solar PV on the other hand result in prices above the ability to pay of Liberians.

It is shown that DG is a promising parallel and complementary tool to the centralized energy policies in place. Both rural electrification and urban service through the expansion of the grid should be approached in complementary ways. The drafting of REMP by the RREA in Liberia provides an opportunity to identify areas in which DG and GE can interface.

It should also be considered that although decentralized rural renewable energy approaches have been proven feasible in other countries, such as Fiji, Nepal, Brazil, and India, implementation programs have not achieved the levels desired. Institutional barriers, high upfront costs, lack of credit, and high cost of appliances are seen as main issues [55–58]. These lessons can be used to inform the REMP and to empower the RREA for a better implementation strategy.

Electrification can play a role in job creation, well-being, urban–rural migration, environmental stewardship, education, and gender issues. Therefore it is recommended that rural electrification programs be included as a part of a wider development agenda [4]. The upcoming development of a second Poverty Reduction Strategy (PRS2) in Liberia can integrate DG and rural renewable technologies as tools towards a sustainable future and development, especially when electricity's key role as a development catalyst is considered.

In particular, the use of biomass for electricity generation can be a key economic incentive for agriculture. Policies can be focused towards increasing income for small and medium farmers through the appropriate use of their food and cash crop waste. However, the use of biomass technology should not interfere with farmers' practices of crop waste management for soil nutrient replenishment. It is important to provide policies that balance both needs.

Education and technical training are key areas where electrification can serve as a catalyst. Provision of electricity needs to be accompanied by educational programs and entrepreneurial training that allow the customers to make better use of electricity [58]. Technologies highlighted in this paper can be used as “seeds” for educational efforts, human capacity building, and business creation.

In the end, economic and technical metrics should leave room for a more complex analysis process. Cultural, social, and economic preferences of Liberians should be considered. Andrade et al. [4] propose that communities should be given autonomy, information, and ownership in the development of the electrification programs.

A significant consideration not addressed in this paper is energy efficiency. The rural residential sector in Liberia can provide opportunities to implement efficiency measures from the onset, which are likely to be more effective. Use of thermal energy for cooking and water heating, for example, is an opportunity for efficiency improvement policies. As the electrification process continues, efficiency can play a significant role in cost reduction and environmental considerations in solutions for the provision of coupled thermal and electric energy.

Financing of a large electrification effort represents a challenge for policy, research, and development. Private–Public partnerships, civil societies, NGO's, and other organizations can be encouraged to enter the electrification market through financing mechanisms that take advantage of carbon markets and development funds. All stakeholders can be encouraged to collaborate to produce innovative financing and implementation programs.

In summary, the GOL and developing organizations can look at the renewable energy potential of Liberia as a way to help the country leap-frog technologies, encourage the protection of their environment, help economic recovery through high quality jobs, lead to a sustainable development economy, open up economic opportunities in the carbon market, and diminish social divides. These factors can help leverage aid dollars to better serve the development of Liberia.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2013.11.017.

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